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Speed Control of the Pentaphase Asynchronous Machine: Comparative Study Between Vector Control with Conventional PI and Fuzzy PI

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Abstract: Controlling asynchronous machines is complex because of the non-linearity of the model and the coupling between stator and rotor quantities. Thanks to advances in power electronics, decoupled control techniques have been developed to reproduce the performance of DC machines, while eliminating mechanical constraints. However, in the case of polyphase machines, these control strategies remain limited due of the harmonics generated by the inverter, which degrade power quality. To address this issue, a new fuzzy logic control strategy is proposed, aimed at reducing parasitic currents and improving dynamic performance in a five-phase asynchronous machine. A comparison between vector control using conventional PI and fuzzy PI is considered, based on the dynamic responses of speed, torque and harmonic distortion rate, especially under load variations and during rotational reversals. The simulation results obtained in MATLAB demonstrate a significant enhancement in speed stability and a reduction in ripples, confirming the effectiveness of the proposed approach.

Keywords: Five-phase asynchronous machine, Vector control, Fuzzy logic, Speed oscillations, Automatic, Engineering electric machine

Introduction

Multiphase asynchronous machines, especially five-phase machines, are attracting growing interest in advanced electrical drive technology, particularly in applications requiring high power density, fault tolerance and torque quality, such as electric vehicles, aeronautics and marine systems. Compared to their three-phase counterparts, polyphase machines offer increased robustness, reduced current harmonics, and the possibility of operation in degraded mode in the event of partial inverter or phase failure. (Barrero, 2015; Duran, 2016).

To take full advantage of these benefits, high-performance control strategies are required. Field-Oriented Control (FOC), developed in the 1970s, revolutionized the control of asynchronous machines at, artificially decoupling torque and flux. This method is based on modeling the machine in a rotating frame of reference (dq) synchronized with the stator or rotor flux, thus transforming the asynchronous machine into a DC machine equivalent. This makes it possible to control flux (via a d-axis component) and torque (via a q-axis component) separately, considerably simplifying the control strategy and improving system dynamics (Xu, 2002; Bermudez, 2017).

However, the performance of vector control can be degraded in the presence of non-linear models, parametric uncertainties or external disturbances. In this context, non-linear control approaches have been explored to improve

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the robustness and stability of the system. Among these, fuzzy control. The fuzzy PI controller combines the structure of the PI controller with the principles of fuzzy logic, allowing dynamic adjustment of proportional and integral gains according to the state of the system. This approach improves the robustness, response speed and stability of the control system, particularly during variations in load and operating conditions.

System Description

Modeling of Five Phase Induction Machine

The voltage model of the five-phase induction motor is obtained as (Iffouzar,2015):

$$\begin{cases} [V_s]_{abcde} = [R_s]_{5.5}[i_r]_{abcde} + \frac{d}{dt}[\psi_s]_{abcde} \\ [V_r]_{abcde} = [R_r]_{5.5}[i_r]_{abcde} + \frac{d}{dt}[\psi_r]_{abcde} \end{cases} \quad (1)$$

Where Vs and Vr are the voltage martices,
i_s , i_r the current vectors according to the five phases. (abcde),
ψ_s, ψ_r the flux vector according to the five phases (abcde), and the subscripts s and r refer to the stator and rotor windings, respectively.

The different stator (rotor) phases are magnetically coupled to each other and also coupled to the rotor (stator) circuits; hence the stator (rotor) flux equations depend on the stator (rotor) loop currents, respectively.

$$\begin{cases} [\psi_s]_{abcde} = [L_s]_{5.5}[i_s]_{abcde} + [M_{sr}]_{5.5}[i_r]_{abcde} \\ [\psi_r]_{abcde} = [L_r]_{5.5}[i_r]_{abcde} + [M_{rs}]_{5.5}[i_s]_{abcde} \end{cases} \quad (2)$$

Avec $[M_{sr}]_{5.5} = [M_{rs}]^t{}_{5.5}$ mutual inductance matrices between the stator and rotor phases. $[L_s]_{5.5}$ et $[L_r]_{5.5}$ are the matrices of the stator and rotor inductances, respectively.

$$\begin{cases} [V_s]_{abcde} = [R_s][i_s]_{abcde} + \frac{d}{dt}\left[[L_s][i_s]_{abcde}\right] + \frac{d}{dt}\left[[M_{sr}][i_r]_{abcde}\right] \\ [V_r]_{abcde} = [R_r][i_r]_{abcde} + \frac{d}{dt}\left[[L_r][i_r]_{abcde}\right] + \frac{d}{dt}\left[[M_{rs}][i_s]_{abcde}\right] \end{cases} \quad (3)$$

The stator inductance matrix is given as follows:

$$[L_s]_{5.5} = \begin{bmatrix} L_{m+}L_{fs} & L_m\cos(\frac{2\pi}{5}) & L_m\cos(\frac{4\pi}{5}) & L_m\cos(\frac{6\pi}{5}) & L_m\cos(\frac{8\pi}{5}) \\ L_m\cos(\frac{8\pi}{5}) & L_{m+}L_{fs} & L_m\cos(\frac{2\pi}{5}) & L_m\cos(\frac{4\pi}{5}) & L_m\cos(\frac{6\pi}{5}) \\ L_m\cos(\frac{6\pi}{5}) & L_m\cos(\frac{8\pi}{5}) & L_{m+}L_{fs} & L_m\cos(\frac{2\pi}{5}) & L_m\cos(\frac{4\pi}{5}) \\ L_m\cos(\frac{4\pi}{5}) & L_m\cos(\frac{6\pi}{5}) & L_m\cos(\frac{8\pi}{5}) & L_{m+}L_{fs} & L_m\cos(\frac{2\pi}{5}) \\ L_m\cos(\frac{2\pi}{5}) & L_m\cos(\frac{4\pi}{5}) & L_m\cos(\frac{6\pi}{5}) & L_m\cos(\frac{8\pi}{5}) & L_{m+}L_{fs} \end{bmatrix} \quad (4)$$

The mutual inductance matrix (Msr) is expressed as follows:

$$[M_{sr}]_{5.5} = L_m \begin{bmatrix} \cos(\theta) & \cos(\theta-\frac{2\pi}{5}) & \cos(\theta-\frac{4\pi}{5}) & \cos(\theta-\frac{6\pi}{5}) & \cos(\theta-\frac{8\pi}{5}) \\ \cos(\theta-\frac{8\pi}{5}) & \cos(\theta) & \cos(\theta-\frac{2\pi}{5}) & \cos(\theta-\frac{4\pi}{5}) & \cos(\theta-\frac{6\pi}{5}) \\ \cos(\theta-\frac{6\pi}{5}) & \cos(\theta-\frac{8\pi}{5}) & \cos(\theta) & \cos(\theta-\frac{2\pi}{5}) & \cos(\theta-\frac{4\pi}{5}) \\ \cos(\theta-\frac{4\pi}{5}) & \cos(\theta-\frac{6\pi}{5}) & \cos(\theta-\frac{8\pi}{5}) & \cos(\theta) & \cos(\theta-\frac{2\pi}{5}) \\ \cos(\theta-\frac{2\pi}{5}) & \cos(\theta-\frac{4\pi}{5}) & \cos(\theta-\frac{6\pi}{5}) & \cos(\theta-\frac{8\pi}{5}) & \cos(\theta) \end{bmatrix} \quad (5)$$

where L_s, L_{fs}, and L_m are stator, stator leakage, and magnetizing inductances, respectively.

The transformation matrix (Pn) for the five-phase induction motor is defined as follows (Menghal,2014):

$$[P_n]=\begin{bmatrix}\cos(\theta) & \sin(\theta) & 0 & \cdots & 0\\ -\sin(\theta) & \cos(\theta) & 0 & \cdots & 0\\ 0 & 0 & 1 & \cdots & 0\\ \vdots & \vdots & 0 & \ddots & 0\\ 0 & 0 & \cdots & \cdots & 1\end{bmatrix} \tag{6}$$

By multiplying the matrix $[P_n]$ by the Concordia matrix $[T]$, we obtain the transition matrix (P), which is a rotating reference frame shifted by the angle φ. This is known as the Park matrix. (Levi,2004).

$$[P]=[P_n][T]=\sqrt{\frac{2}{5}}\begin{bmatrix}\cos(\varphi) & \cos(\varphi-\frac{2\pi}{5}) & \cos(\varphi-\frac{4\pi}{5}) & \cos(\varphi-\frac{6\pi}{5}) & \cos(\varphi-\frac{8\pi}{5})\\ -\sin(\varphi) & -\sin(\varphi-\frac{2\pi}{5}) & -\sin(\varphi-\frac{4\pi}{5}) & -\sin(\varphi-\frac{6\pi}{5}) & -\sin(\varphi-\frac{8\pi}{5})\\ 1 & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) & \cos\left(\frac{12\pi}{5}\right) & \cos\left(\frac{16\pi}{5}\right)\\ 0 & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{8\pi}{5}\right) & \sin\left(\frac{12\pi}{5}\right) & \sin\left(\frac{16\pi}{5}\right)\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix} \tag{7}$$

$[P_n]$: Rotary matrix
(T) : Generalised Concordia Matrix.
(P) : Generalised Park matrix
After applying Park's transformation matrix to the stator and rotor equations, the five-phase system can be decomposed into a dq coordinate system plus an additional xy coordinate system.

The stator and rotor voltage equations for the 5-phase induction motor are written in the dq axis as follows (Levi, 2004).

Stator voltages — Rotor voltages

$$\begin{cases}V_{ds}=r_s i_{ds}-\omega_s\psi_{qs}+\frac{d}{dt}\psi_{ds}\\ V_{qs}=r_s i_{qs}+\omega_s\psi_{ds}+\frac{d}{dt}\psi_{qs}\end{cases}\qquad \begin{cases}V_{dr}=r_r i_{dr}-\omega_s\psi_{qs}+\frac{d}{dt}\psi_{ds}\\ V_{qr}=r_r i_{qr}+\omega_s\psi_{dr}+\frac{d}{dt}\psi_{qr}\end{cases} \tag{8}$$

The flow equations become:

$$\begin{cases}\psi_{ds}=(L_m+L_{fs})i_{ds}+L_m i_{dr}\\ \psi_{qs}=(L_m+L_{fs})i_{qs}+L_m i_{qr}\end{cases} \tag{9}$$

The model of the 5-phase asynchronous machine can be completed by the expression of the electromagnetic torque Cem given as follows:

$$C_{em}=P\frac{M}{L_r}\left(\psi_{dr}i_{qs}-\psi_{qr}i_{ds}\right) \tag{10}$$

To study dynamic behaviour, the following equation of motion has been added:

$$J\frac{d\Omega}{dt}=C_{em}-C_r-f\Omega \tag{11}$$

Fuzzy Control

Fuzzy control was introduced as an intelligent and flexible approach. Based on the theory of fuzzy sets developed by Lotfi Zadeh in 1965, it allows human reasoning to be reproduced through linguistic rules of the type 'If... then...'. Fuzzy rules link the output signal to the input signals through linguistic conditions, and the establishment of these rules is generally based on the operator's experience and/or the expertise of the control engineer. Fuzzy logic is therefore particularly well suited to controlling and adjusting processes that are difficult to model or control using conventional (Menghal,2014). The fuzzy controller adjusts control signals (such as voltage or current) in real time based on variations in error and its derivative, enabling **automatic adaptation** to changes in load, speed or operating conditions.

Speed Regulator

Figure 1 illustrates the speed control structure of a five-phase induction motor (IM), which comprises three control loops: the angular speed control loop Ω, managed by a fuzzy PI controller, and two additional fuzzy PI controllers regulating the stator flux ψ_s and the electromagnetic torque C_{em} . The reference electromagnetic torque is generated directly from the outer speed loop.

These two controllers produce the stator reference voltages (V_{dsref}, V_{qsref}) along the d and q axes. Applying the inverse Park transformation yields the actual stator voltages that drive the motor to produce the desired speed. The estimator receives as input the measured stator currents (i_{ds} , i_{qs}), obtained via the Park transformation. From these, the estimation block computes the instantaneous stator flux amplitude ψ_s , the electromagnetic torque C_{em} and the stator electrical angle θ_s.

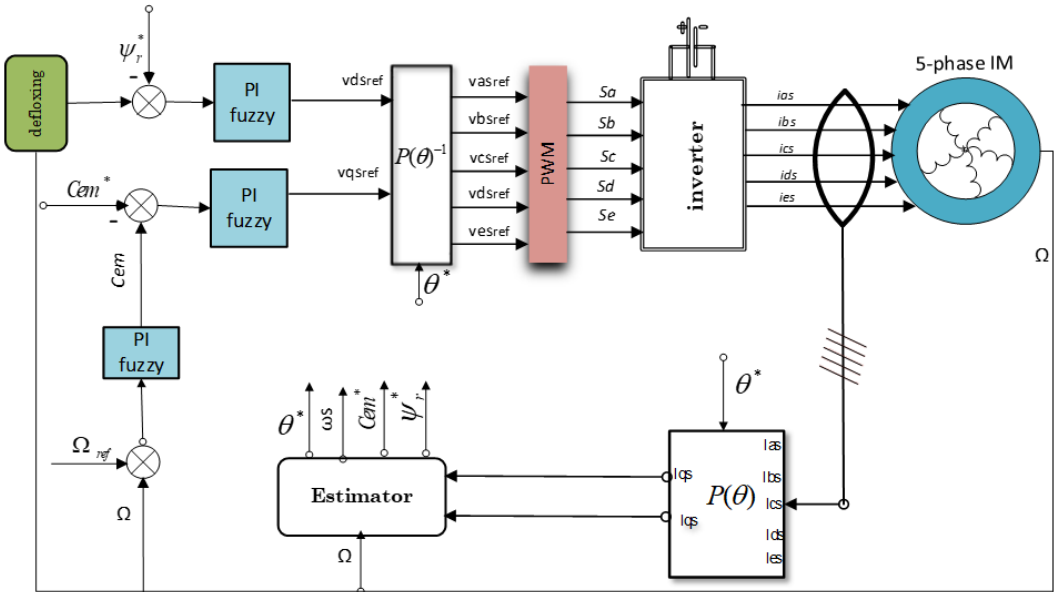

Figure 1. Overall structure of MASP speed control using fuzzy PI controllers

Simulation Results

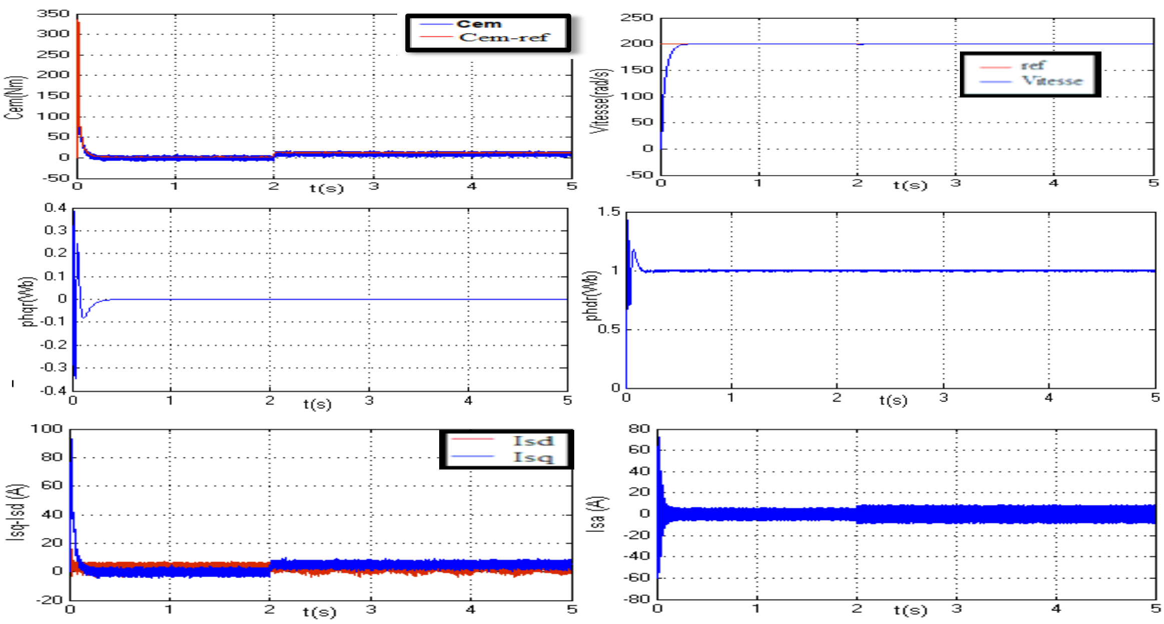

Figure 2. Fuzzy logic speed control followed by application of load Cr = 10 N·m and time t = 2 s.

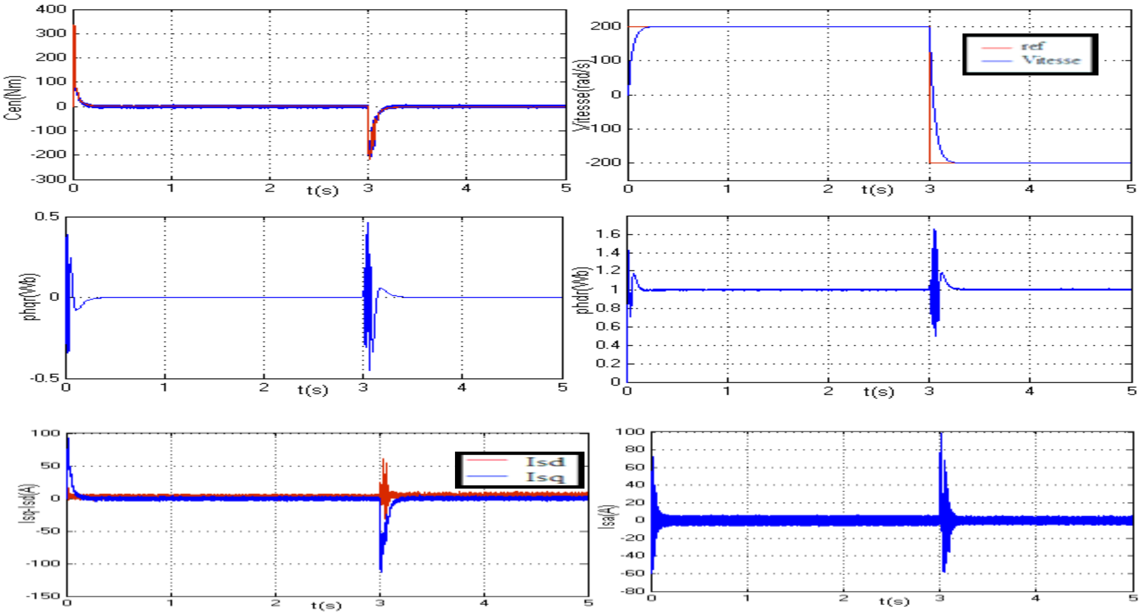

Figure 3. Fuzzy control of the MASP with reversal of the direction of rotation of the speed

Robustness Test

To evaluate the robustness of vector control based on fuzzy PI controllers for MASP speed regulation, a parameter variation is introduced by increasing the rotor resistance Rr to 1.25Rr at t=3 seconds. Figure 4 illustrates the system's response during start-up, under the application of a resistive load torque, followed by the change in rotor resistance, when speed control is implemented using a Fuzzy PI-type controller. From the results presented in Figure 4 , it can be observed that the rotor flux-oriented vector control exhibits strong robustness against parameter variations. The dynamics of setpoint tracking and the decoupling performance of the machine remain unaffected, confirming the adaptability and effectiveness of the proposed control approach.

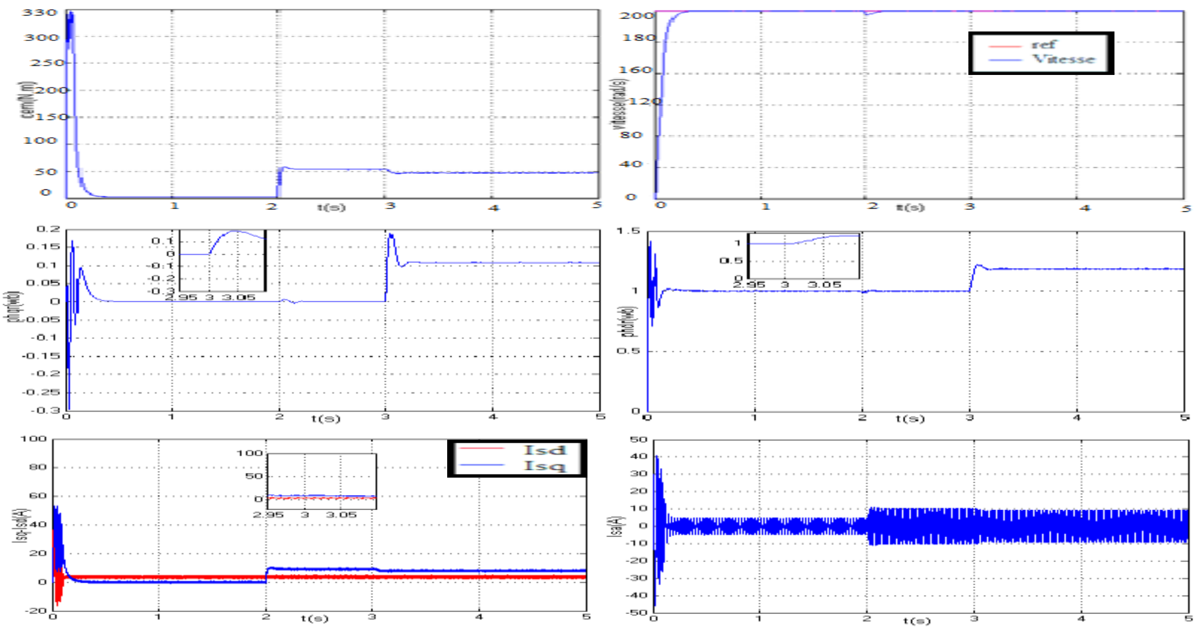

Figure 4. Dynamic behaviour of the MASP during start-up with parametric variation

Comparative Study of Control

We will also discuss the influence of load application on the five-phase machine to conduct a comparative study between PI and fuzzy PI control on the dynamic responses of speed, electromagnetic torque and currents.

Vector control by Fuzzy PI controller Vector control by PI controller

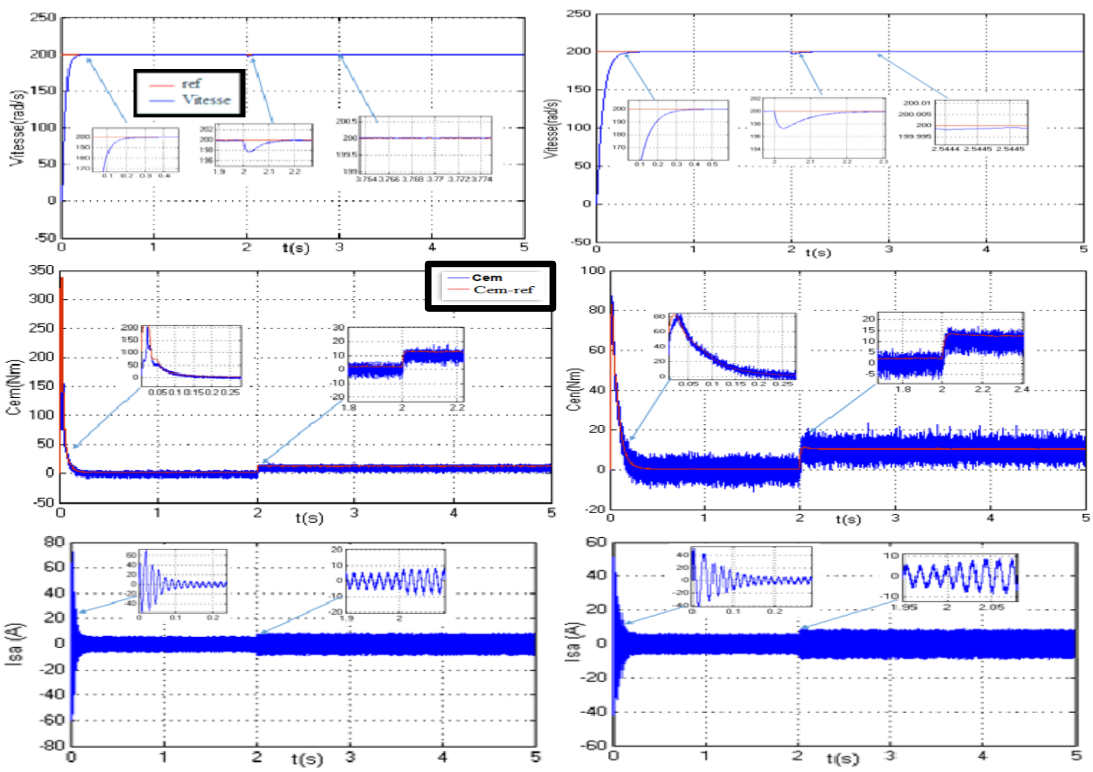

Figure 5. Comparative study between PI and fuzzy PI control for speed adjustment when applying a load torque (Cr = 10 N.m) at time t = 2s.

Simulation Results and Discussion

The results show that the behaviour of the two controllers is identical during steady-state conditions, but the fuzzy controller offers more advantages:

- Improved response time.
- Rapid disturbance rejection.
- Speed perfectly tracks its reference.

With fuzzy logic control, the starting torque reaches a value of Cem=330N.m, unlike vector control, which has a torque of Cem=86.7N.m. The comparison between the results obtained by the two different types of controllers shows that the dynamic responses of the machine are better for fuzzy controllers, which demonstrates the effectiveness of the fuzzy control algorithm used.

Harmonic Distortion Rate

In a variable speed drive, the inverter, whether current or voltage supplied by a rectifier, always operates at a variable frequency. It produces, in the rectified current and consequently in the current of the network that supplies it, harmonics that are not integer multiples of the network frequency calculated by the THD. The total harmonic distortion (THD) is an indicator of the quality of signal processing in a device. It is given by the following expression:

$$THD = \sqrt{\frac{\sum_{n}^{\infty} H(n)^2}{H(1)}}$$

$H1$**:** Amplitude of the fundamental component, whose frequency is w_0.
$H(n)$**:** Amplitude of the nth harmonic, whose frequency is nw_0 .

The following figure shows the current THD Isa for both types of control.

Fuzzy control vector control

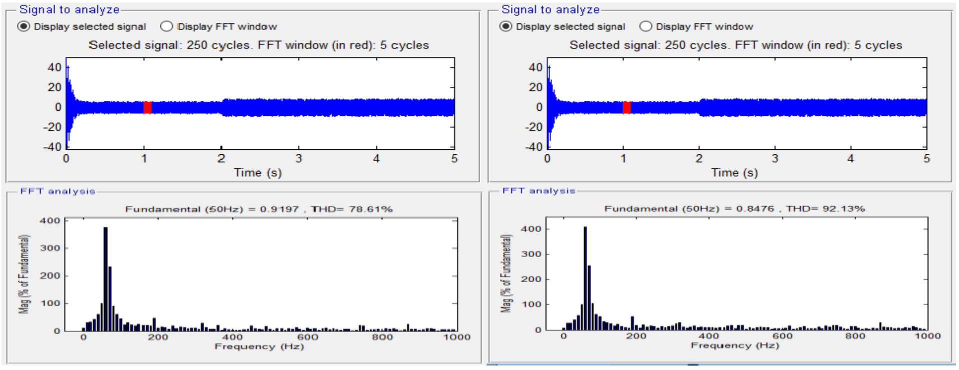

Figure 6. Isa current harmonic spectrum for fuzzy control and vector control

Table 1. Table of results

Types	THD	Fundamental
Fuzzy control	78.61%	0.9197
Vector control	92.13%	0.8476

Interpretation of Results

Figure 6 shows the harmonic spectra of the source current with the application of two types of control. There is a 78.61% improvement in current THD for fuzzy control, which proves its effectiveness compared to vector control.

Conclusion

The approach proposed in this work exploits the process of optimizing PI controller gains using fuzzy logic applied to a five-phase asynchronous machine under real-time operating conditions in order to determine the optimal voltage vector that guarantees the desired tracking speed at high torque and with less ripple. Vector control with fuzzy PI control is a high-performance evolution of conventional PI control for polyphase asynchronous machines. It combines the precision of vector decoupling with the adaptive intelligence of fuzzy logic, paving the way for more efficient, reliable, and autonomous drive systems. According to the simulation results, the fuzzy PI controller offers the best convergence towards optimal solutions with rapid rejection of disturbances, proving its effectiveness in solving complex control problems.

Scientific Ethics Declaration

* The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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